A non-drag-free gravitational-wave mission architecture

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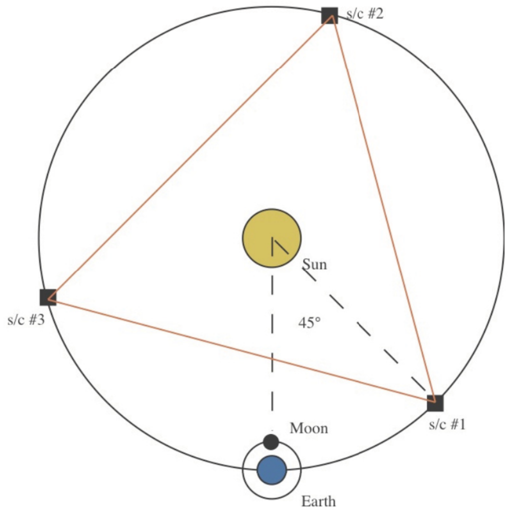
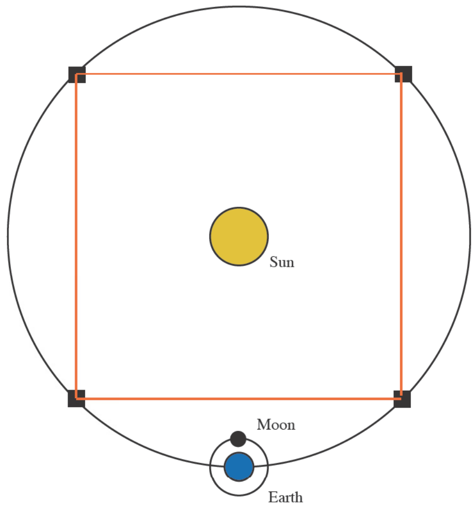
#1: Which concept should be studied? Triangle or square?





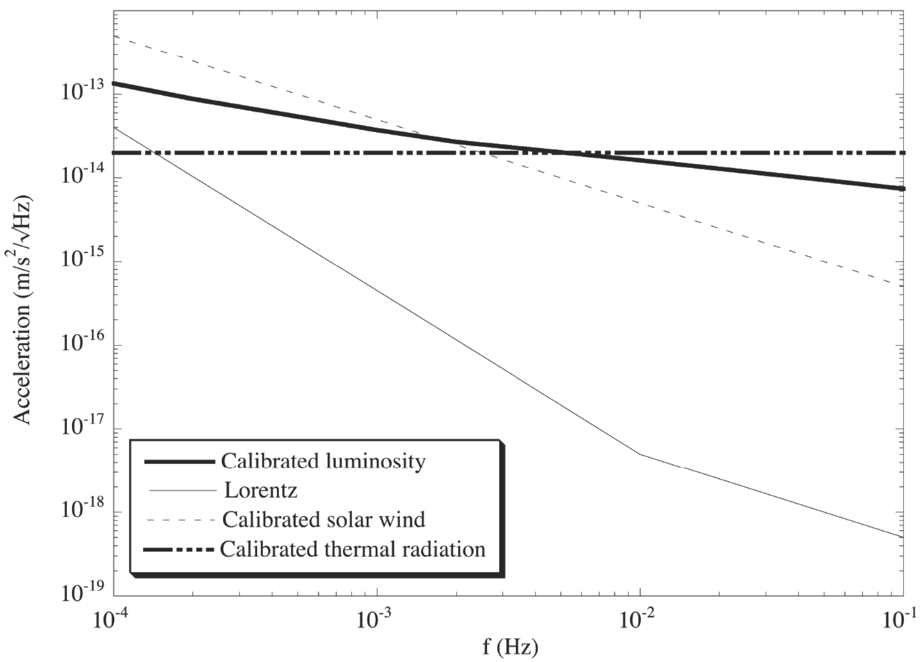
- The cost of 3 dual-string spacecraft with 6 telescopes/instruments should cost about the same as 4 single-string spacecraft with 8 telescopes/instruments
- For purposes of response to the RFI request for cost, mass, etc estimates based on on engineering work, analogies to the GRAIL mission with 2 single-string spacecraft recently launched will be more credible than creating a 3-spacecraft mission from thin air.
- Because the cost of the payload is the largest unknown, if a Team-X study is undertaken a study of the 3 spacecraft option is recommended

#2: Would the Disturbance Free Payload described in the RFI By Shao, et al. be applicable to this concept?

- No. The Shao et al. concept includes a drag-free system, albeit with possibly coarser control, but that spacecraft positions control is counter to the non-drag-free approach where NO thrusting is used during science operations.

#3: Without drag-free, the noise budget is sensitive to noisy forces and mechanical disturbances on the spacecraft that are difficult to rule out on the ground and measure/model in space (e.g. Pioneer Anomaly). Are these controllable? What is the budget for unmodeled forces?

- Noise budget needs to be done for any GW mission
- Leading terms are discussed in paper, but more work needs to be done
- Unknown forces cannot be modeled, so there is always some risk;
  - A drag-free sensor has similar risks
- Note that there is good evidence that 'Pioneer anomaly' is well explained by spacecraft thermal model



Solar calibrated to voltage standard noise
Solar wind calibrated to 1%
Solar panel temperature controlled to 0.1 mK
(and assumes Earth environment (GRAC
Lorentz force based on 30 V potential

Not shown are:
Surface outgassing
Thruster leakage

#4: Do you have an estimate of what delta-v is required for each spacecraft and how long the cruise phase will last?

- A simple calculation for a 3.5 year transit time to 180 degrees from Earth gives delta-v required = 2*1.43 km/s
  - one maneuver of 1.43 km/s at launch to reduce orbit period to 7/8 year, and similar maneuver to circularize

- Taking spacecraft mass of 350 kg, using Hall thruster (Busek BHT-600) with 42 mN thrust, Isp 1585 s, then 138 days of thrusting is required for each maneuver
- Total propellant mass is 65 kg

- GRAIL spacecraft dry mass is 200 kg, propellant mass is 100 kg
  - Assume non-drag-free spacecraft mass is 250 kg, 64 kg propellant mass, leaving 36 kg.

- GRAIL spacecraft peak power is 700 W

#5: What comm. capability is required? What antenna sizes are required onboard and at the ground station? Would you consider lower sampling because of the lower frequency response?

- 1.25 m spacecraft antenna using X-band with 17 W transmitted power to a DSN 34m antenna gives a data rate > 15,000 bits/second
  - Antenna field of view is sufficient to see Earth at all times with no articulation
- Suggested data rate is 1500 bits/second, 130 Mb/day
  - 2.5 hours of contact per day (or 7.5 hours every third day) would get data down
- This data rate based on 2000 ESA Final Technical Report
  - LISA sensitivity might be achievable with larger telescope or shorter wavelength laser, so assume same interferometer data rate
    - Limited at low frequencies by binary confusion noise
  - No drag free sensor or control system, but similar data volume assumed for solar pressure, thermal, solar wind. etc. calibration data

Simple telemetry link calculation

Transmitter Parameters				
	RF Power, dBm	42.30		
	(Watts)		17.00	
	Transmit Circuit Loss, dB	-1.00		1 is typical conservative value
	Antenna Circuit Loss, dB	-0.50		.5 is typical conservative value
	Antenna Gain, dBi	38.24		
	Antenna diameter, m		1.25	
	Wavelength, cm		3.40	3.4 cm is X-band
	Efficiency		0.50	0.5 is typical
	Pointing Error, dB	-1.00		related to how far off beam center
	Total :	78.05		
Path Parameters:				
	Space Loss, dB	-280.90		
	Range, km		3.00E+08	
	Atmospheric Atten, dB	-0.50		
	Total:	-281.40		
Receiver Parameters:				
	Polarization Loss, dB	-0.50		
	Antenna Gain, dBi	68.39		
	Antenna diameter, m		34.00	
	Efficiency		0.70	
	Pointing Loss, dB	-1.00		
	Noise Spectral Dens, dBm/Hz	-183.83		
	System Temp, K		30.00	
Power Summary:				
	Received Power, dBm	-136.46		
	Received Pt/N0, dB-Hz	47.37		
	SNRV(1-sec)	330.49		
Telemetry:				
	Bit Rate, dB-Hz	44.77		
	Bit Rate, bps	30000.00		Really Symbol rate, typically 2* (information rate)
	Data Power / Total Power, dE	0.00		
	Tlm Mod Index, deg	90.00		
	TLM Rcvr Losses, dB	0.00		
	Eb/N0, dB	2.60		Symbol margin, needs to be >2 typically

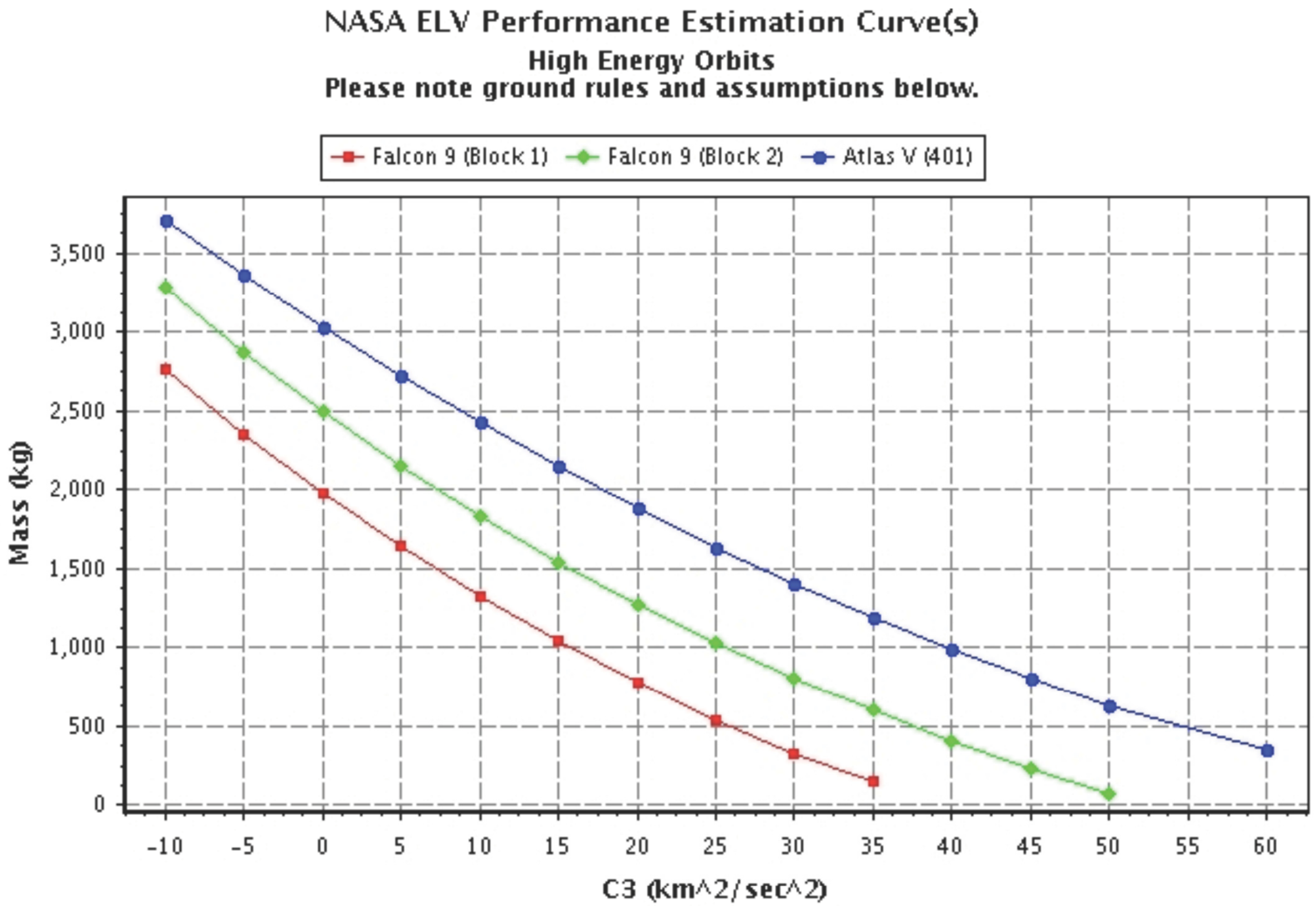
6: Do you have an estimate of the total launch mass, and a candidate launch vehicle?

- Assume single-string spacecraft launch mass = 350 kg
  - GRAIL spacecraft dry mass = 200 kg
  - Additional payload mass = 35 kg
  - Propellant = 65 kg
  - Contingency = 50 kg
- Mass of 4 single-string spacecraft = 1400 kg
- Mass of launch adaptors (2x GRAIL) = 300 kg

- Launch mass 1700kg + margin

- For launch to C3 ~ 1 km^2/s^2, Falcon-9 block -2 or Atlas V-401 would work
  - Falcon 9 Block 2 launches ~2400 kg to C3 ~1
  - Atlas V 401 launces ~2900 kg to C3 ~1
- With 3 dual-string spacecraft Falcon-9 Block 1 might suffice
  - Falcon-9 block 1 launches ~1900 kg to C3 ~ 1

- From NASA launch services web site
- http://elvperf.ksc.nasa.gov



7: Where do the cost savings come over the SGO-Mid concept?

- SGO-Mid requires drag-free sensor and micro-newton thrusters
  - If LISA Pathfinder is successful, and NASA mission acquires GRS from Europe, GRS cost might cost $50M- $100M, and thruster development might cost >$10M
  - If NASA mission does not use Pathfinder contractors, or Pathfinder is not successful, then development of NASA drag-free system might require a flight demonstration, so cost could be very high.
- Other than GRS, the non-drag-free system reduces number of actuators, complexity of interferometry, demanding requirements on spacecraft
  - Team-X study not likely to correctly reflect cost of meeting drag-free requirements

Assembly	SGO-Mid	Non-Drag-Free
Point ahead actuator	Yes	No
IFO back-link	Yes	No
Stablity requirement	50 pm >	1 nm
S/C Mass balance	Yes	No
Telecon steering	Yes	No
GRS	Yes	No
¨N thrusters	Yes	No